A Failure Propagation Modeling Method for Launch Vehicle Safety Assessment

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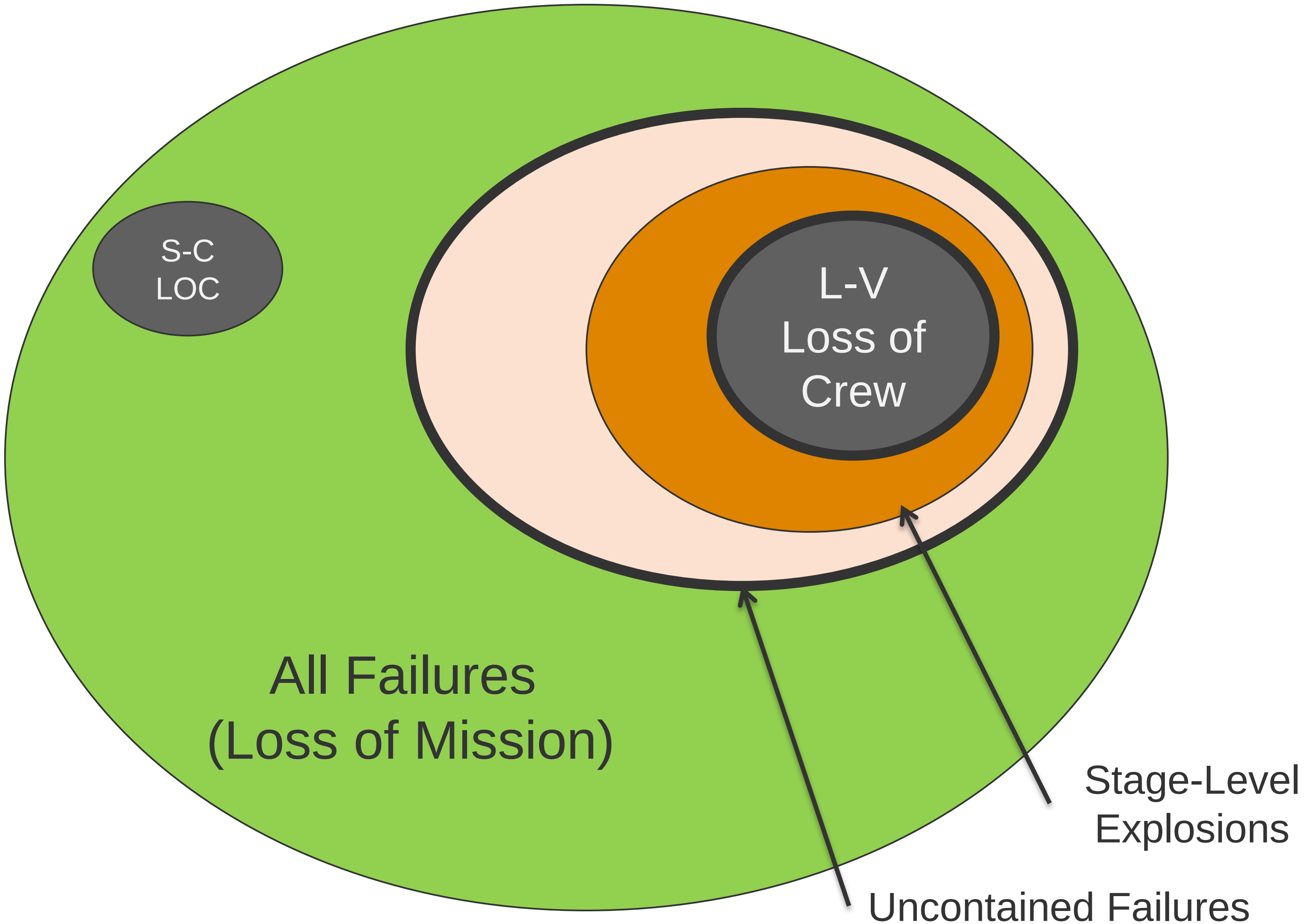
Applied Modeling and Simulation Series
NASA Ames Research Center, November 4, 2014

Presented at the 12th Probabilistic Safety Assessment and Management (PSAM12), June 24, 2014

Outline

- Introduction
  - Role of failure propagation in abort effectiveness assessment
- Method Description and Sample Problem
  - Propagation Process
  - Implementation Enhancements
  - Developing Transition Probabilities
  - Some Example Analyses
- Conclusions and Future Work

Abort Effectiveness In a Nutshell (Avocado?)



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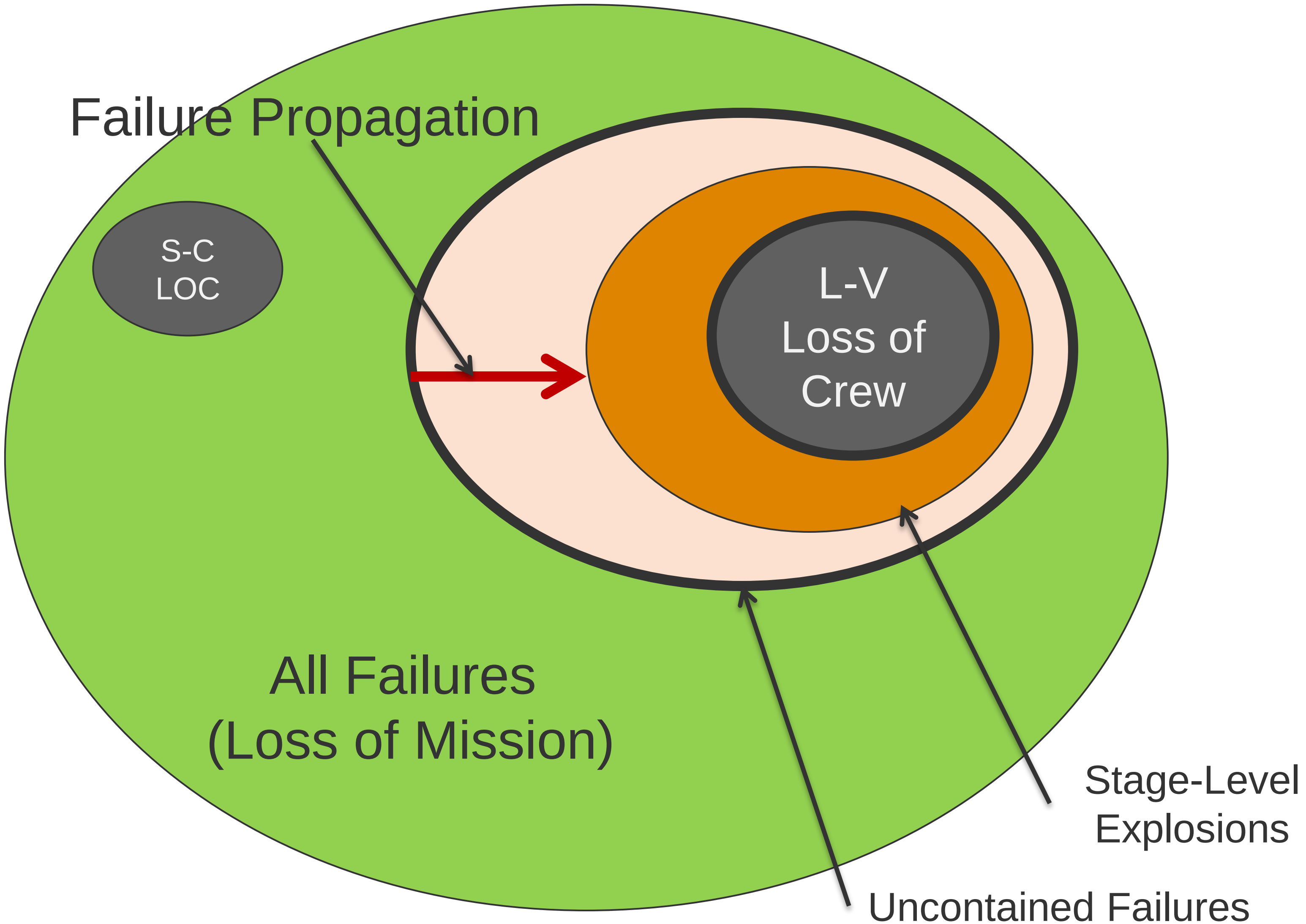
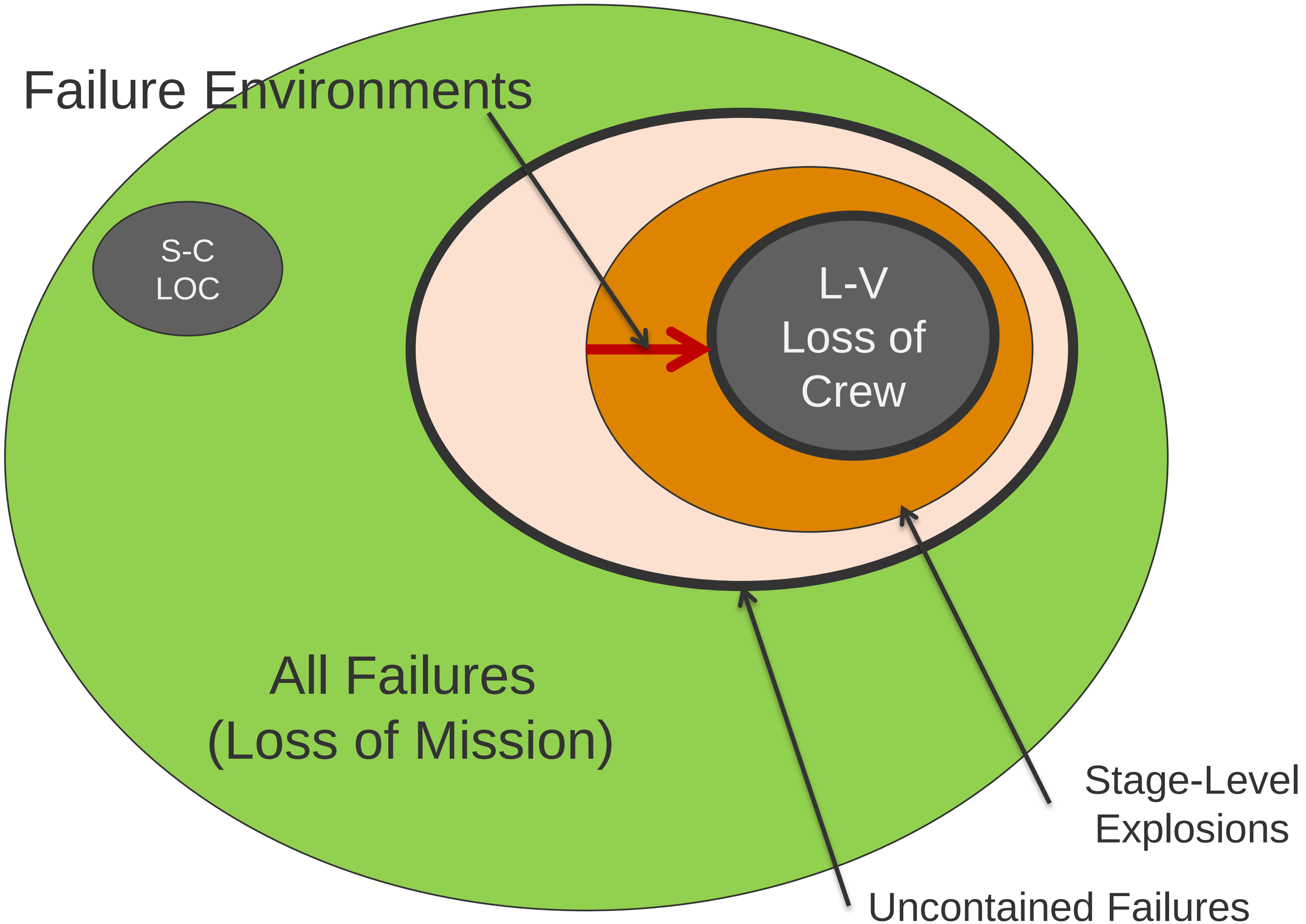


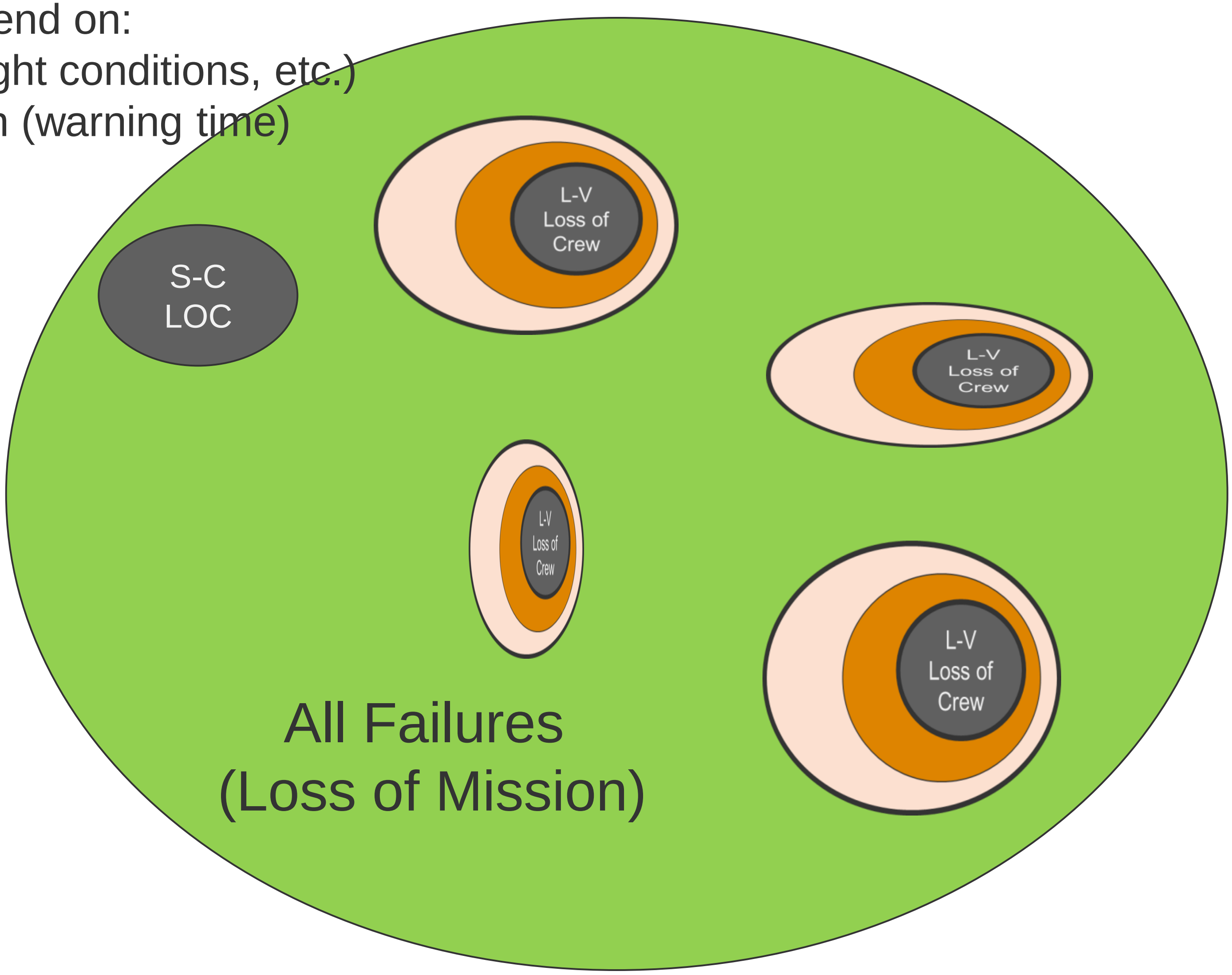
Abort Effectiveness In a Nutshell (Avocado?)



Some of the Complexities

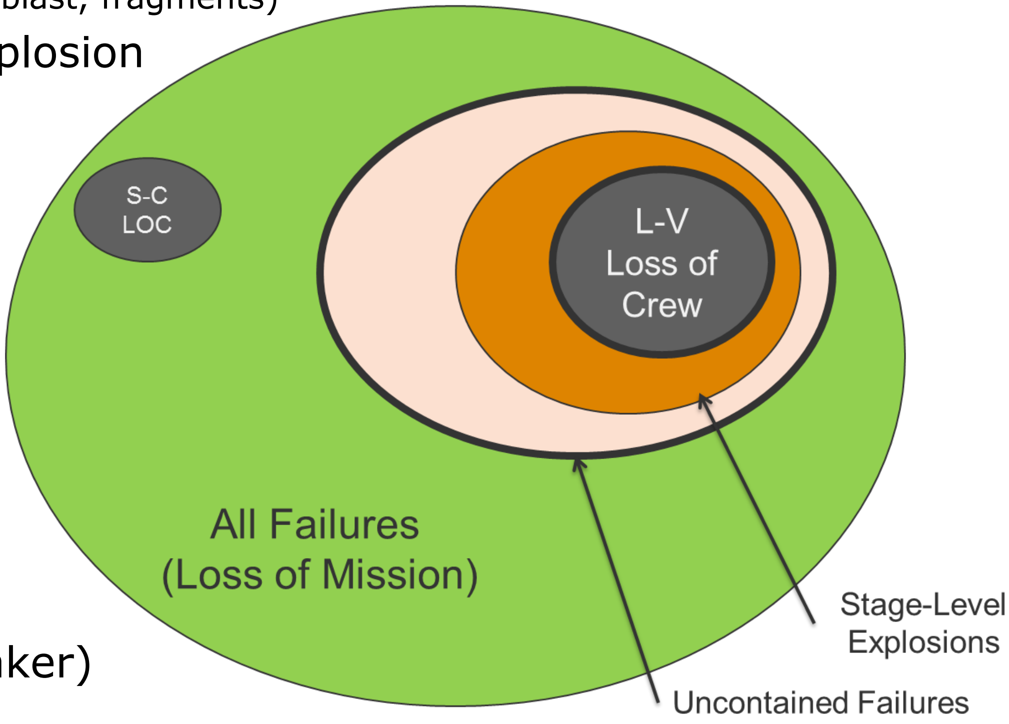
Reality: There are flavors of uncontained, each with its own character
LOC fraction will depend on:

- Mission time (flight conditions, etc.)
- Failure detection (warning time)



Historical Context

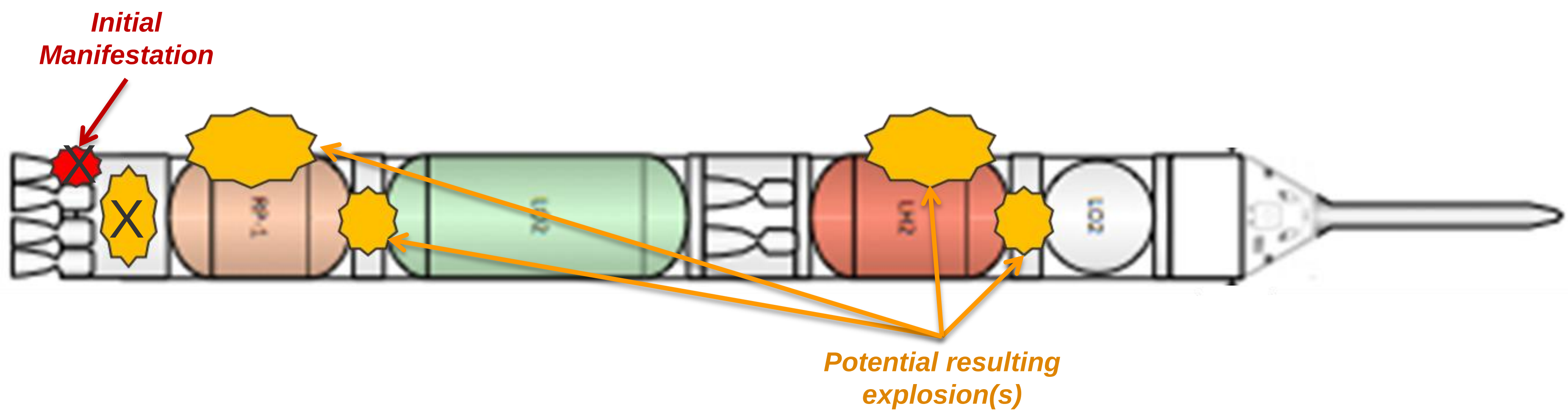
- **ESAS**
  - LOC = 0.15*LOM
- **Ares 1 Upper Stage Engine**
  - Early: All uncontained → Stage Explosion
    - Focus was on environment characterization (blast, fragments)
  - Late: 30% uncontained → Stage Explosion
    - Based on analysis by Ken Gee
- **SLS Complexity**
  - Liquid first stage
    - Multiple engines
    - Confined volume
  - Strap-on boosters
- **SLS Core Stage Engine**
  - Early: 50% → Stage Explosion (weaker)
  - Current: Why we're here



Abortability Example

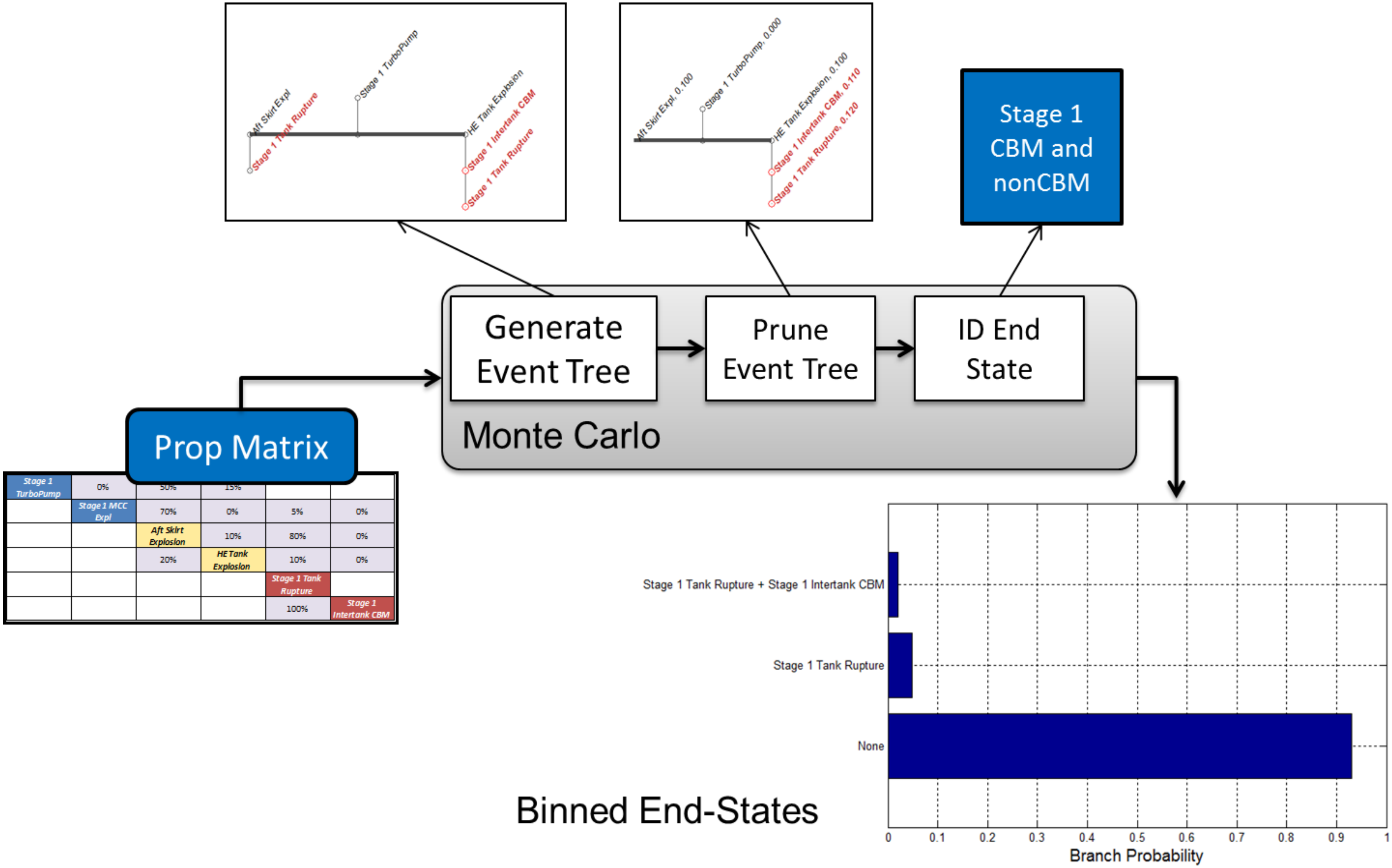
- What is likelihood that, given a main engine turbo-pump burst failure, there will serious injury or death of one or more crew members?
  - What is the likelihood that there will be a “large” explosion (explosion of full stage)?
  - What is the likelihood that a large explosion will critically damage the crew module?

  - How does it vary with mission time?
  - How does it vary with warning time?



- Note: importance of propagation depends on proximity of crew module.

Failure Propagation Model Overview



Stage 1 TurboPump	0%	50%	15%		
	Stage 1 MCC Expl	70%	0%	5%	0%
		Aft Skirt Explosion	10%	80%	0%
		20%	HE Tank Explosion	10%	0%
				Stage 1 Tank Rupture	
				100%	Stage 1 Intertank CBM

Simple Propagation Matrix Example

Selected initiator: Stage 1 turbopump failure

Paths go horizontally and then vertically

Transition Probabilities

Stage 1 TurboPump	0%	50%	15%			
	Stage 1 MCC Expl	70%	0%	5%	0%	
		Aft Skirt Explosion	10%	80%	0%	
		20%	HE Tank Explosion	10%	5%	
				Stage 1 Tank Rupture		50%
				100%	Stage 1 Intertank CBM	
						Stage 2 Tank Rupture

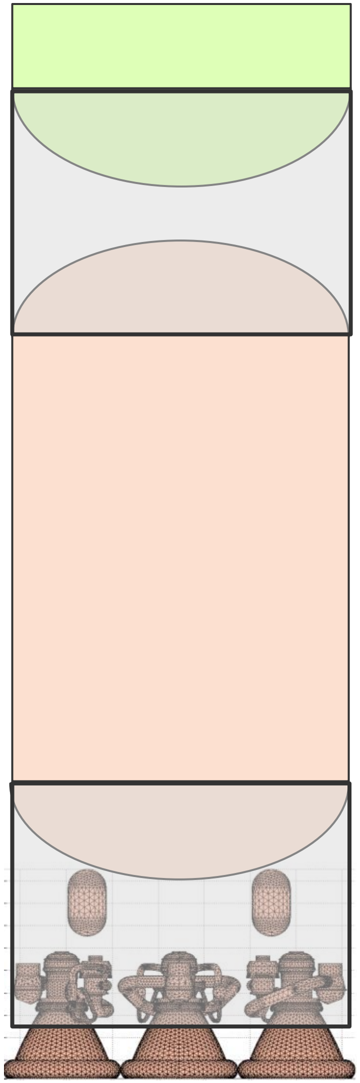
$\underbrace{\text{Stage 1 TurboPump} \quad \text{Stage 1 MCC Expl}}_{\text{Initiators}}$

$\underbrace{\text{Aft Skirt Explosion} \quad \text{HE Tank Explosion}}_{\text{Intermediate Environments}}$

$\underbrace{\text{Stage 1 Tank Rupture} \quad \text{Stage 1 Intertank CBM} \quad \text{Stage 2 Tank Rupture}}_{\text{Failure Environments}}$

Event Tree

Stage 1 TP



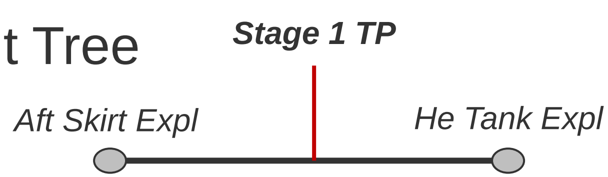
Simple Propagation Matrix Example

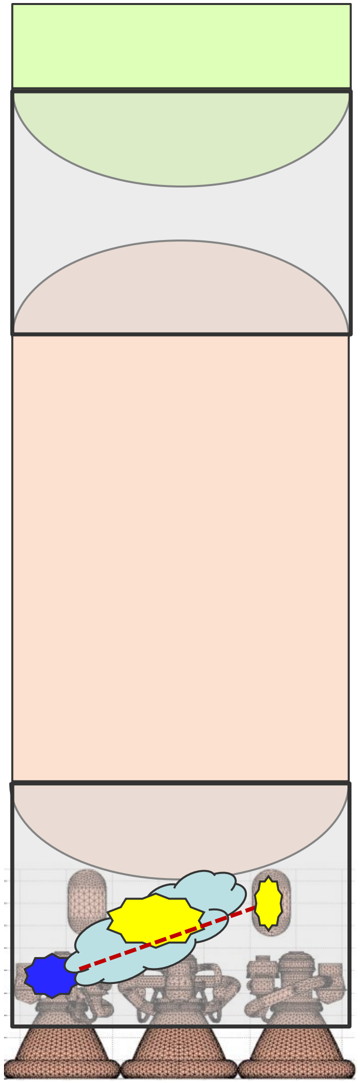
Stage 1 TP burst causes (leakage) aft skirt explosion

Stage 1 TP burst causes (fragment strike) He tank explosion

Stage 1 TurboPump	0%	50%	15%			
	Stage 1 MCC Expl	70%	0%	5%	0%	
		Aft Skirt Explosion	10%	80%	0%	
		20%	*HE Tank Explosion*	10%	5%	
				Stage 1 Tank Rupture		50%
				100%	*Stage 1 Intertank CBM*	
						Stage 2 Tank Rupture

Event Tree

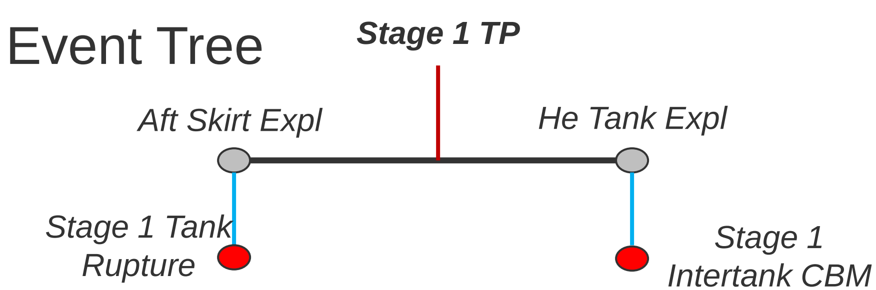


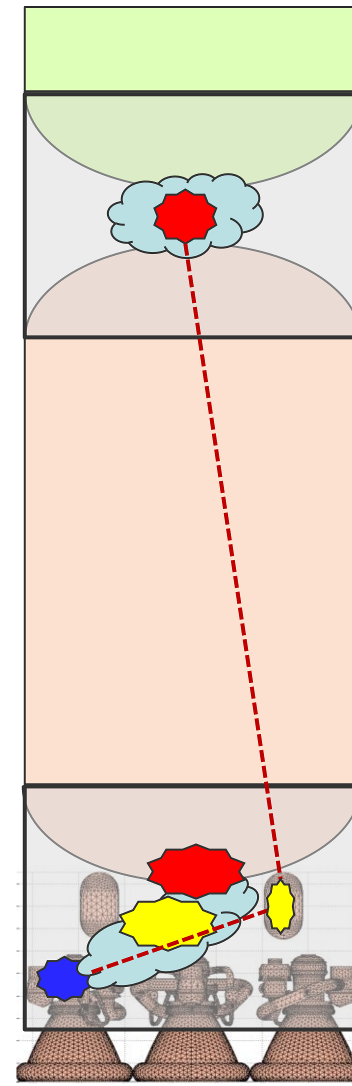


Aft skirt explosion causes (overpressure) Stage 1 tank rupture

He tank explosion causes (fragment) Stage 1 inter-tank CBM

Stage 1 TurboPump	0%	50%	15%			
	Stage 1 MCC Expl	70%	0%	5%	0%	
		Aft Skirt Explosion	10%	80%	0%	
		20%	***HE Tank Explosion***	10%	5%	
				Stage 1 Tank Rupture		50%
				100%	***Stage 1 Intertank CBM***	
						Stage 2 Tank Rupture

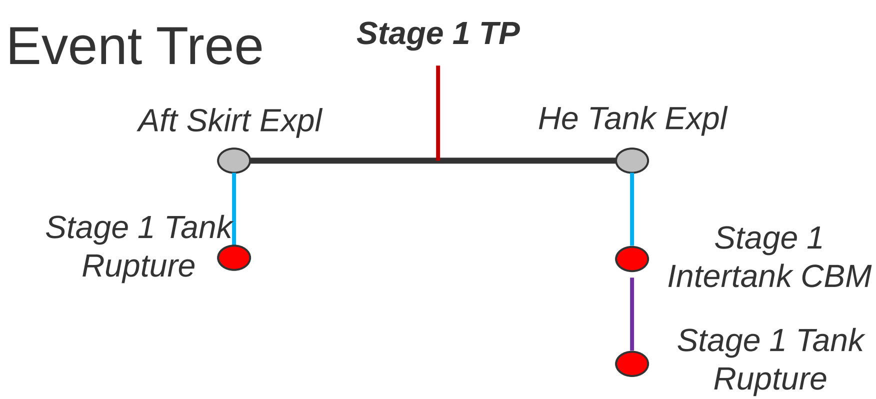


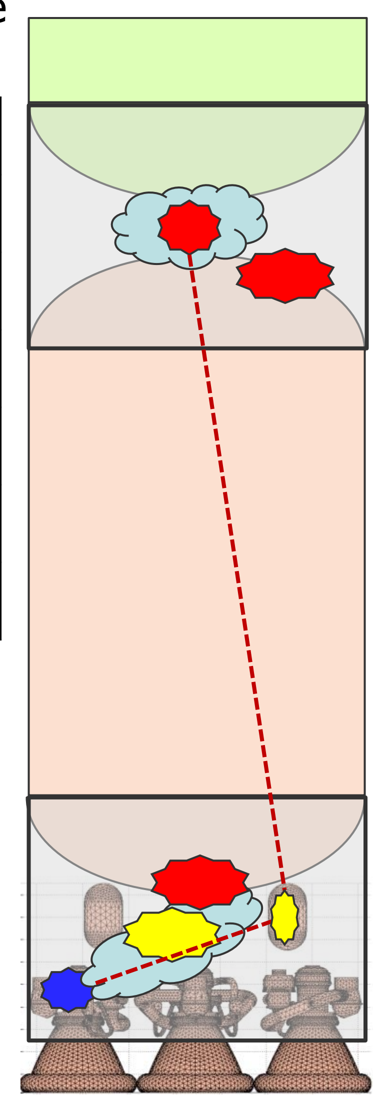


Simple Propagation Matrix Example

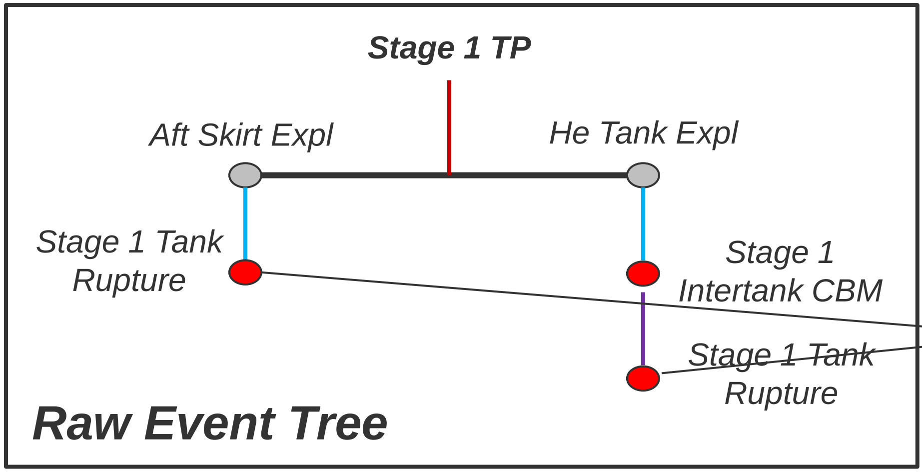
Stage 1 inter-tank CBM causes (overpressure) Stage 1 tank rupture

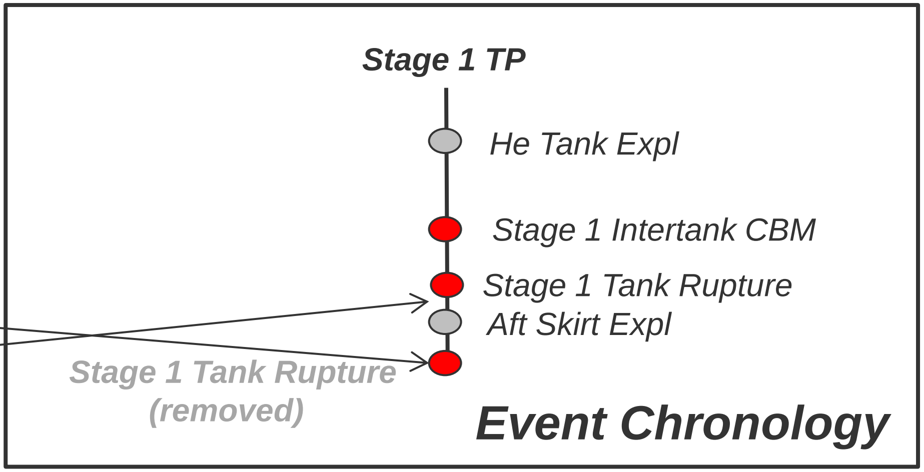
Stage 1 TurboPump	0%	50%	15%			
	Stage 1 MCC Expl	70%	0%	5%	0%	
		Aft Skirt Explosion	10%	80%	0%	
		20%	HE Tank Explosion	10%	5%	
				Stage 1 Tank Rupture		50%
				100%	Stage 1 Intertank CBM	
						Stage 2 Tank Rupture



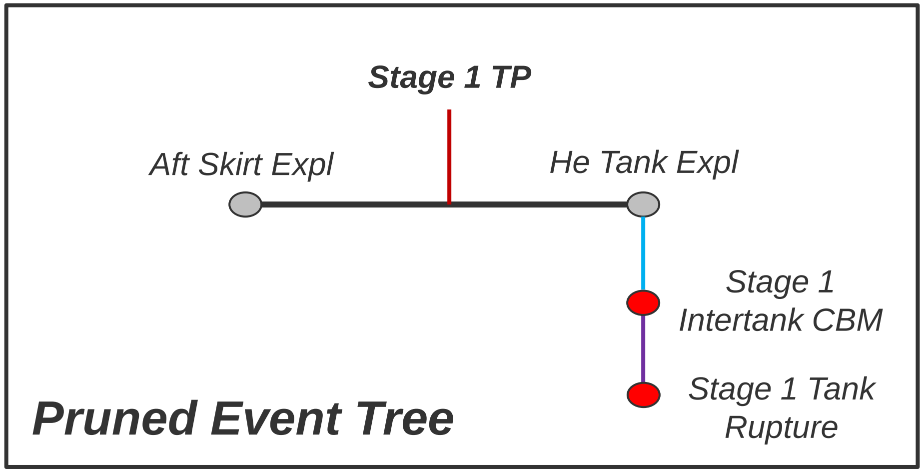


Tree Pruning



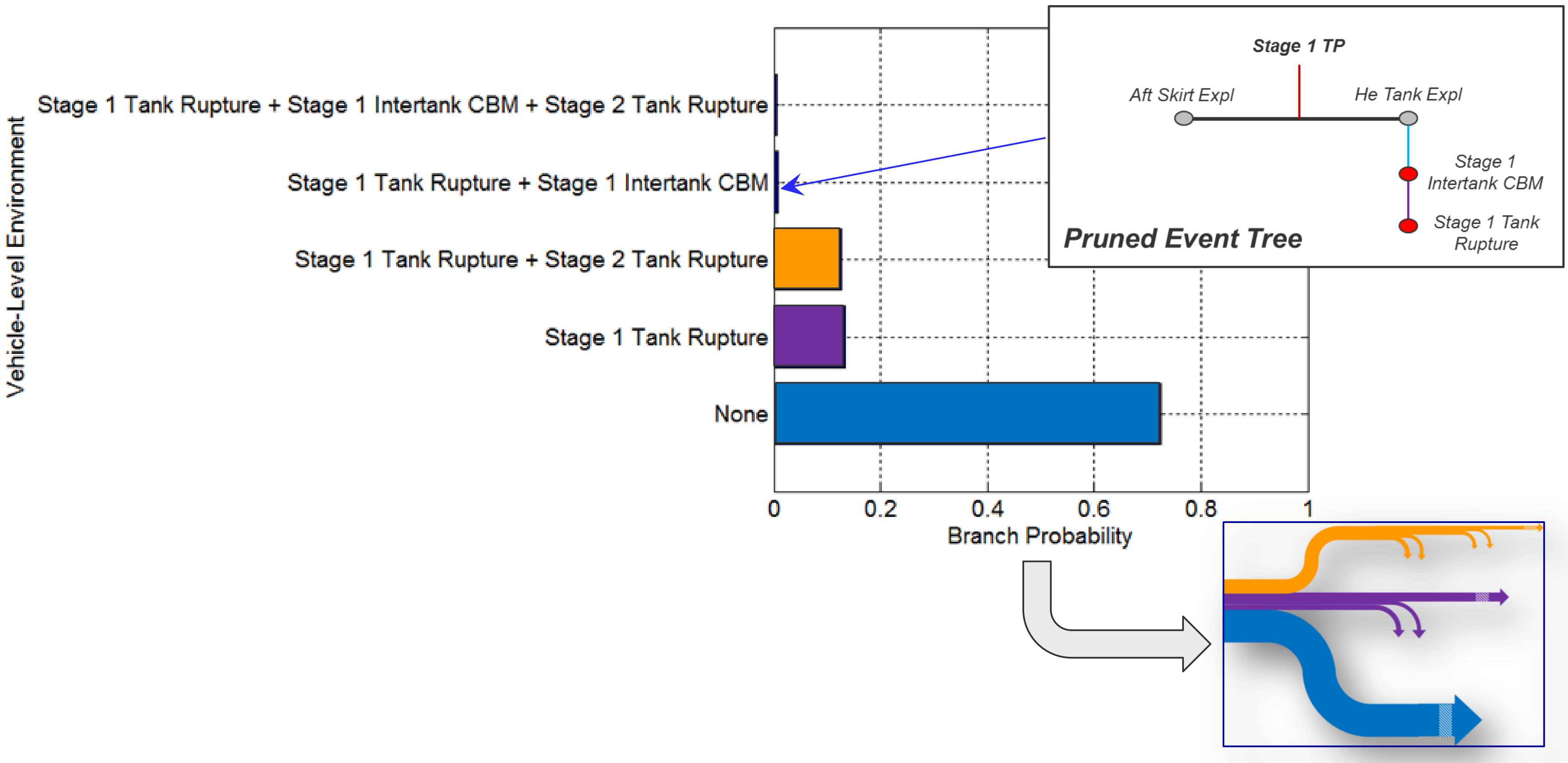


Transition times introduced to enable chronology-based pruning



Sample Monte Carlo Results

Monte Carlo results are binned to produce the desired mapping (branch splits) between the initial manifestation and the explosion(s)

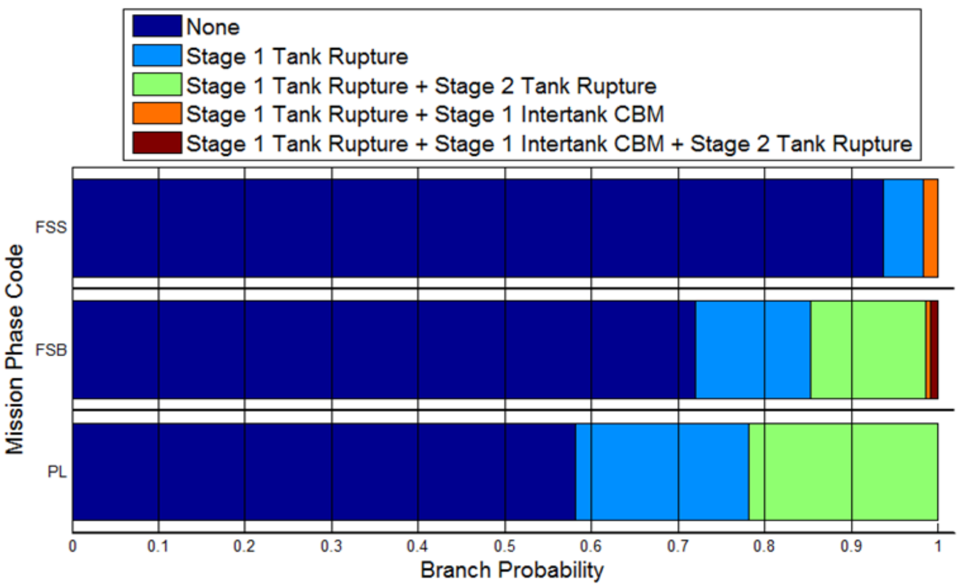


Implementation for Complex Cases

Transition Data Table Snippet

Phase and propagation resistance sensitivities

	Pre-Launch w/ LAS	*First Stage Burn*	*Staging*	*Upper Stage Burn, w/ LAS*	*Upper Stage Burn, no LAS*	*Spacecraft Staging*			
ID	**PL**	**FSB**	**FSS**	**USL**	**USN**	**USS**	**Source**	**Target**	**Timing**
E6	0/ 0/ 0	0/ 0/ 0	0/ 0/ 0	0//	0//	0//	Stage 1 TurboPump	Stage 1 MCC Expl	0.01/0.01
F6	90/50/15	90/50/15	90/50/15	0//	0//	0//	Stage 1 TurboPump	Aft Skirt Expl	0.1/0.1
G6	25/15/5	25/15/5	25/15/5	0//	0//	0//	Stage 1 TurboPump	HE Tank Explosion	0.1/0.1
F7	100/70/20	100/70/20	100/70/20	0//	0//	0//	Stage 1 MCC Expl	Aft Skirt Expl	0.1/0.1
G7	5/0/0	5/0/0	5/0/0	0//	0//	0//	Stage 1 MCC Expl	HE Tank Explosion	0.01/0.01
H7	100/15/0	15/5/0	0//	0//	0//	0//	Stage 1 MCC Expl	Stage 1 Tank Rupture	0.01/0.01
I7	0//	0//	0//	0//	0//	0//	Stage 1 MCC Expl	Stage 1 Intertank CBM	0.1/0.1



Mapping: Dependence on Phase

Stage 1 Shutdown/Separation

Stage 1 Boost

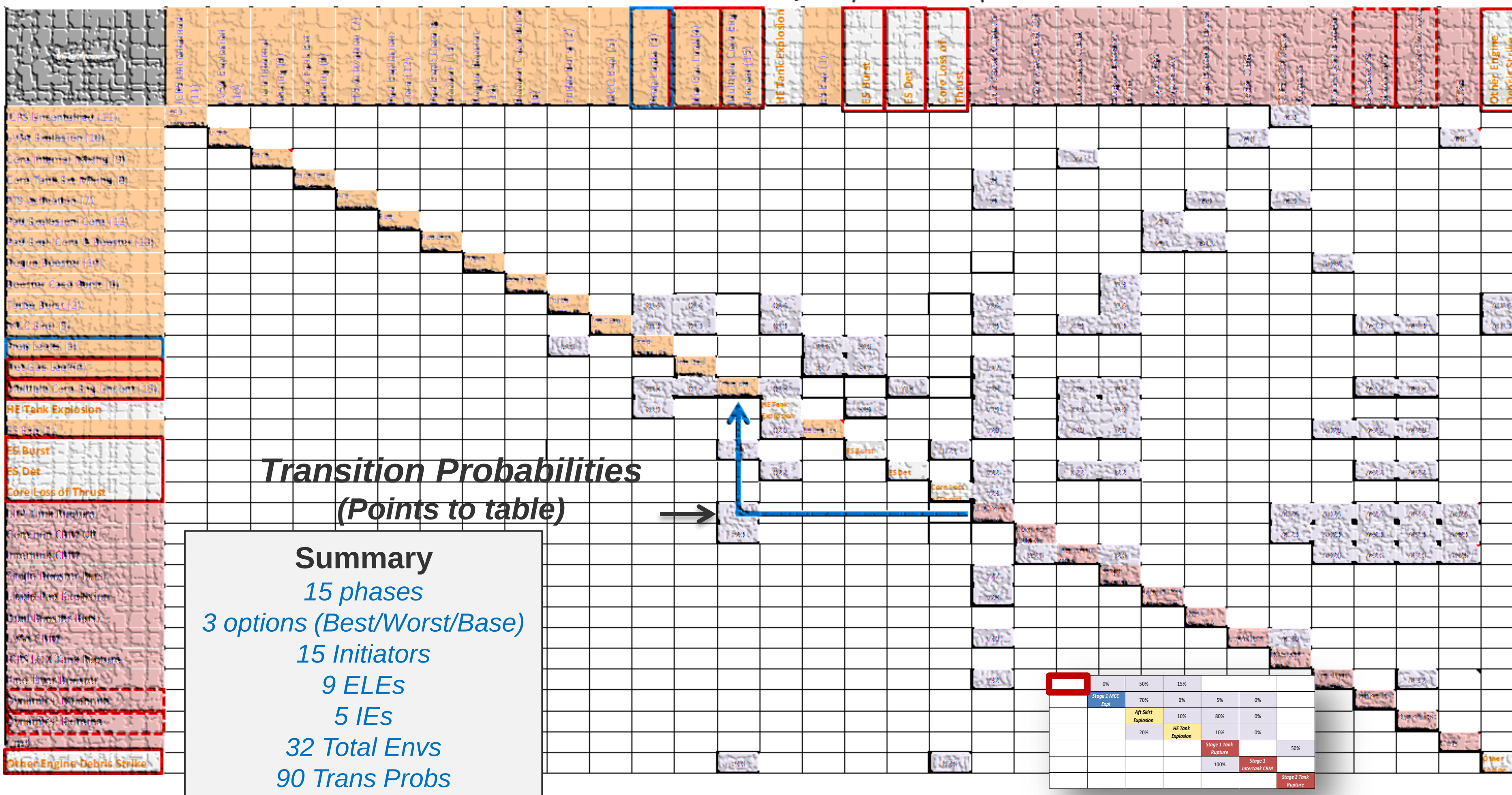
Pre-Launch

SLS Propagation Graph

Intermediate Environments
(Facilitate propagation)

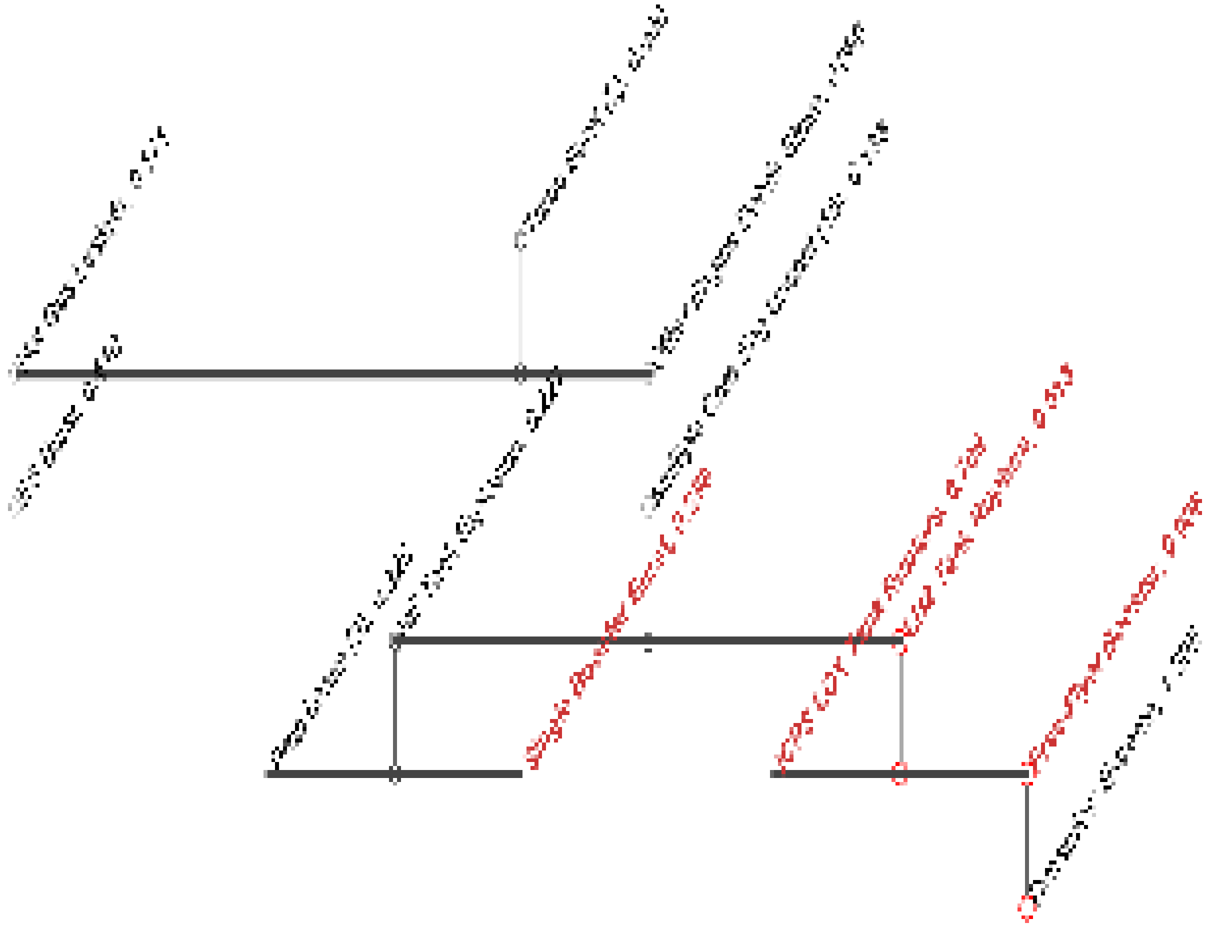
Initiators/Initial Manifestations
(Tables)

Element-Level Environments
(Direct threat to Crew/CM)



Summary
15 phases
3 options (Best/Worst/Base)
15 Initiators
9 ELEs
5 IEs
32 Total Envs
90 Trans Probs

Example of Complex Failure Event Tree



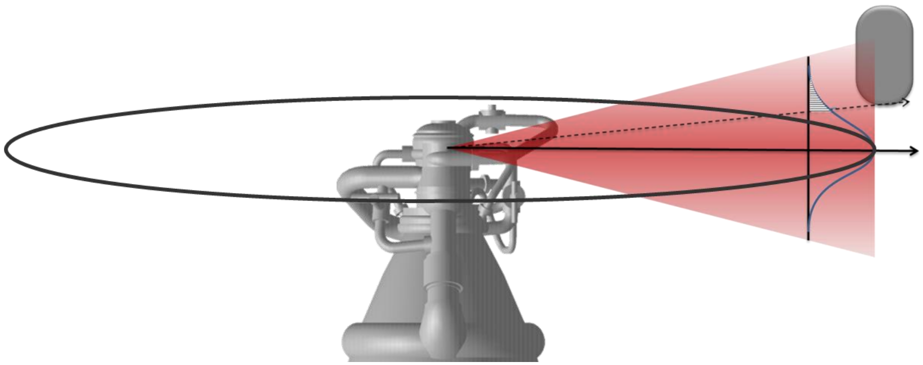
5-stage process

11 triggered environments (not including initiator)

4 triggered explosion types

Transition Analysis Thought Process

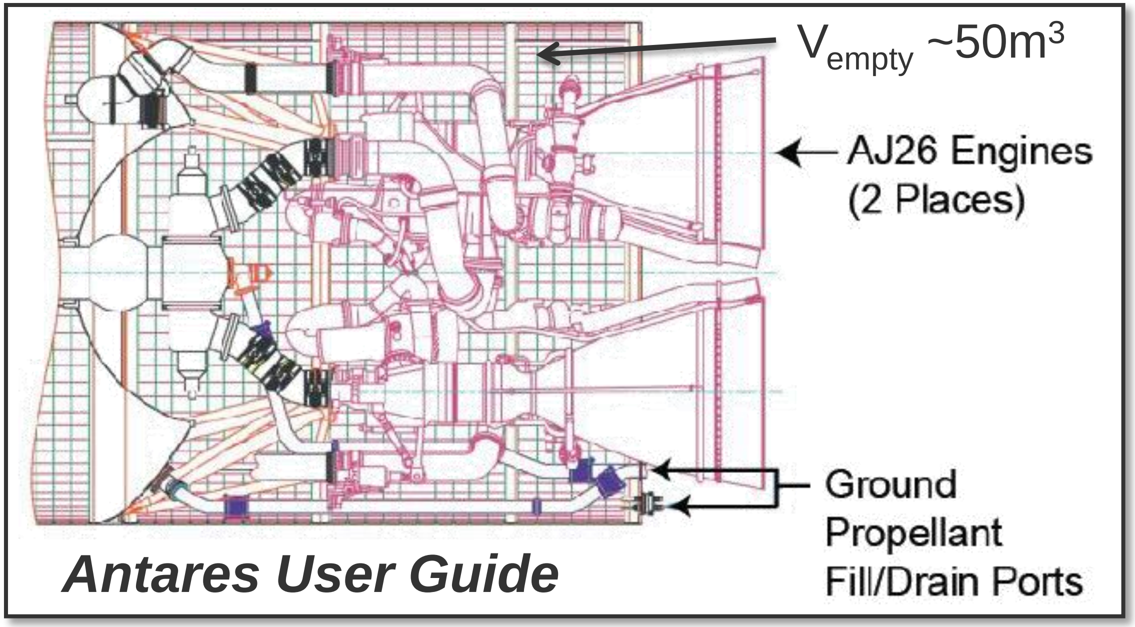
- Energy Transfer Mode(s)
  - Overpressure
  - Kinetic Energy (Fragments)
  - Shock & Vibration
  - Environment (pressure, temperature)
  - Etc.
- Source Severity
  - Energy type: ***[KE]***
  - Magnitude: ***[Velocity and density]***
  - Uncertainties: ***[Velocity and density]***
- Target Vulnerability
  - Energy type: ***[KE]***
  - Magnitude: ***[Size, Location, Limit velocity]***
  - Uncertainties: ***[Limit velocity]***
- Energy Decay
  - Natural decay with distance: ***[1/d²]***
  - Obstructions: ***[%]***



Example: TP Burst → He tank burst

Engine Section Propagation

- Modes
  - Fragments
    - Uncontained engine failures
    - COPV bursts (subsequent to being struck), assumed uniform in all directions
  - Overpressure
    - MCC explosion
    - COPV burst
  - Leaks
    - Propellant
    - Hot Gas
      - -TP pre-burners
      - -MCC
    - COPV burst
- Primary Outcomes
  - LH2 Tank Rupture
    - Core nonCBM
  - ES Burst (rupture)
    - Damage to nozzle propellant lines→ multiple engines uncontained or loss of thrust
  - Multiple engines uncontained
    - Many consequences
  - Core loss of thrust
    - LH2 tank rupture (when boosters on and burning)



Conclusions and Future Work

Status

- Propagation model has been implemented
  - Complex interactive process modeled with a number of simpler interactions
  - Automatically generates potentially complex failure event sequences
- Advantages
  - Facilitate communication with engineers regarding consequences of failure
  - Enables complex mission phase behavior to be captured
  - Tracks and accumulates failure evolution times (where available)
  - Easy to set up easy problems but can be expanded to more complex problems
- Currently being used in support of the Space Launch System (SLS) and Commercial Crew programs

Potential Enhancements

- More automated transition probability evaluation
- Integration with CAD-based simulation methodology

Antares Failure: October 28, 2014

T+14.7s

Plume changes color (ΔMR)

+ <1 s

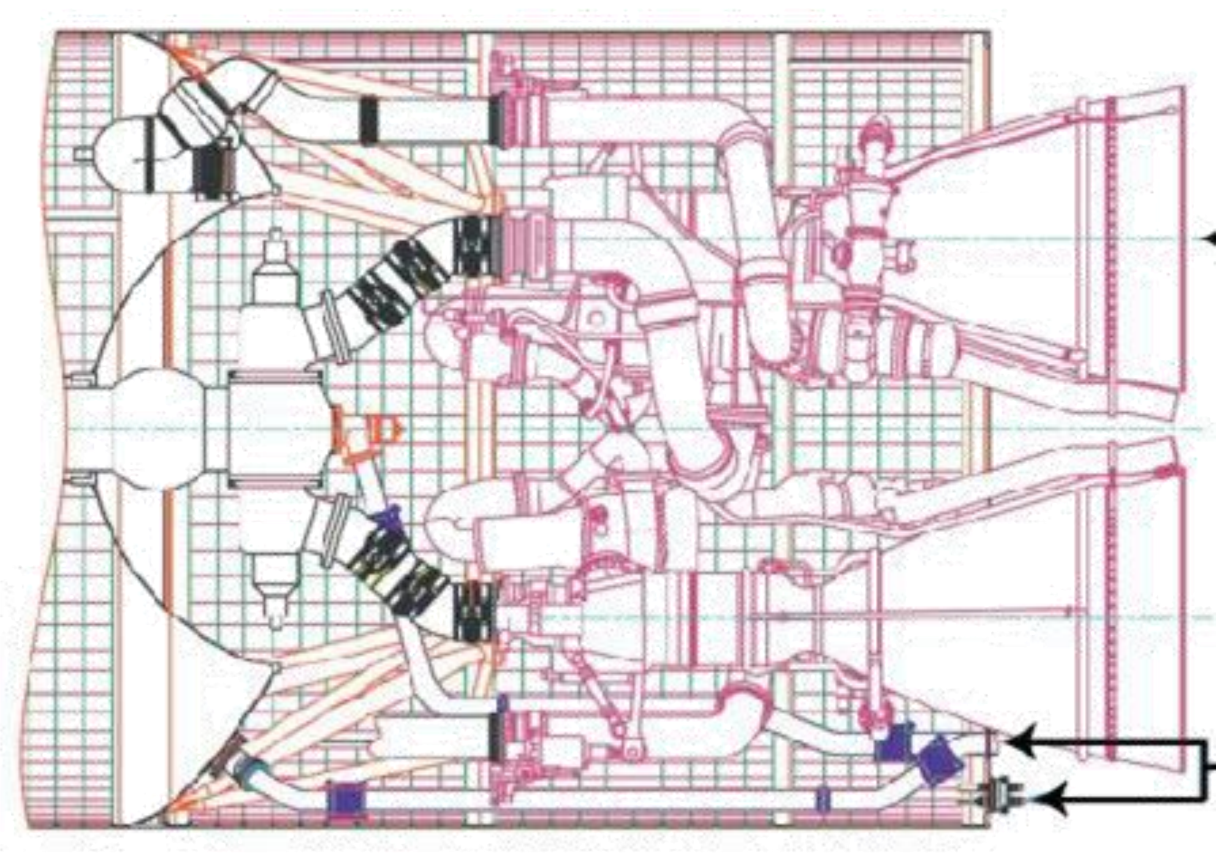
R.U.D.

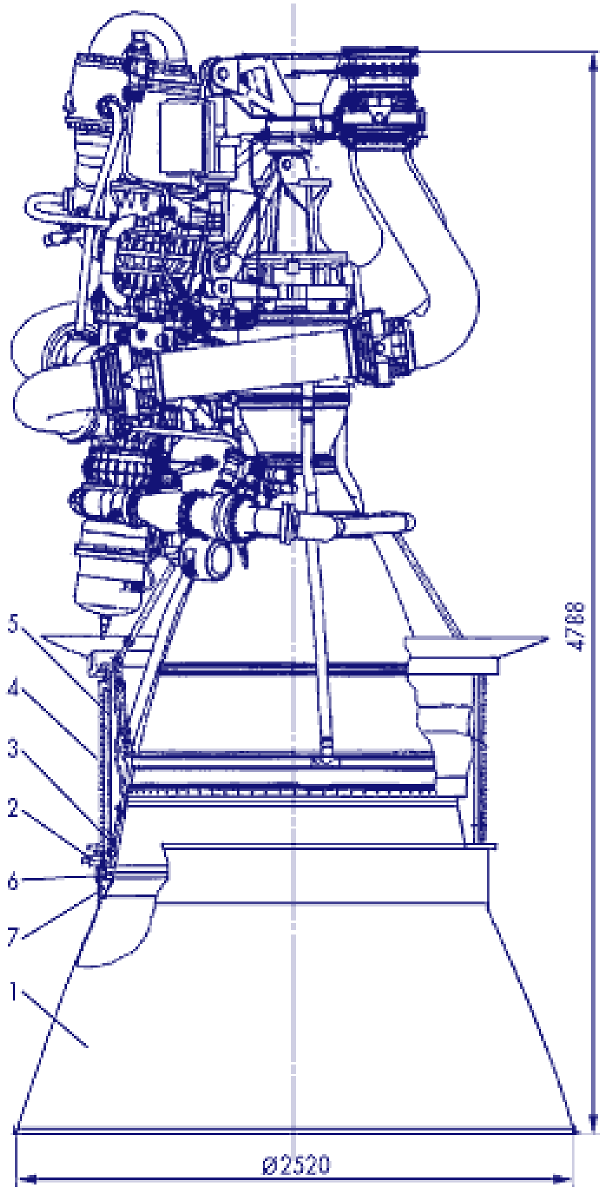
FTS @ T+20s

http://www.spaceflight101.com/cygnus-orb-3-mission-updates.html

Orbital Sciences Antares Rocket

Antares Engine Section





AJ-26 Engines

- Antares powered by dual AJ-26 engines
  - LOX-Kerosene
  - Staged combustion
- Both engines on this flight were manufactured for the Soviet N1 rocket in the 1960s and 1970s
- Conversion to AJ-26 involved:
  - Updated electronics for new electromechanical valve actuators
  - Modifications to fuel systems
  - Added hydraulic TVC system
- Acceptance tests were performed for each engine
  - One minute burn
  - Failure in May during one of these acceptance tests
    - Described as an explosion
  - Failure in 2011
    - Kerosene leak leading to fire
    - Traced to stress corrosion cracks in metal